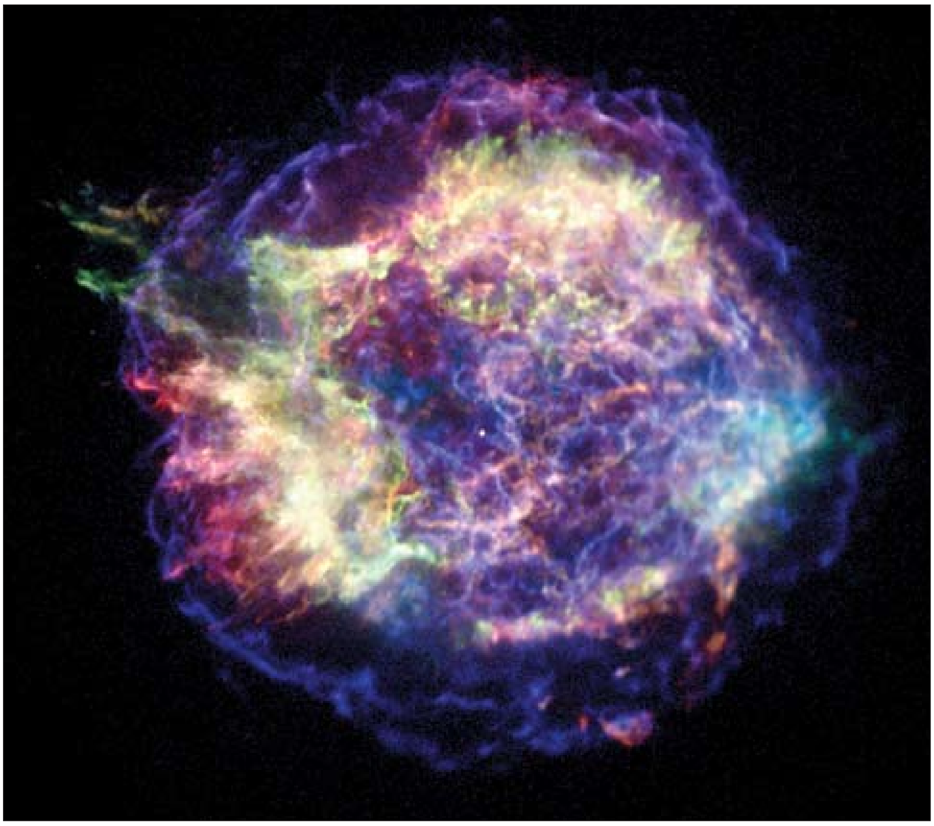
Cosmoclimatology: a

Henrik Svensmark draws attention to an overlooked mechanism of climate change: clouds seeded by cosmic rays.

Abstract

Changes in the intensity of galactic cosmic rays alter the Earth's cloudiness. A recent experiment has shown how electrons liberated by cosmic rays assist in making aerosols, the building blocks of cloud condensation nuclei, while anomalous climatic trends in Antarctica confirm the role of clouds in helping to drive climate change. Variations in the cosmic-ray influx due to solar magnetic activity account well for climatic fluctuations on decadal, centennial and millennial timescales. Over longer intervals, the changing galactic environment of the solar system has had dramatic consequences, including Snowball Earth episodes. A new contribution to the faint young Sun paradox is also on offer.



1: Cosmic rays (relativistic electrons) stirring in the Cassiopeia A supernova remnant make the wispy blue lines of energetic X-ray emissions seen by NASA's Chandra X-ray Observatory. (NASA/CXC/UMass Amherst/M D Stage *et al.*)

Data on cloud cover from satellites, compared with counts of galactic cosmic rays from a ground station, suggested that an increase in cosmic rays makes the world cloudier. This empirical finding introduced a novel connection between astronomical and terrestrial events, making weather on Earth subject to the cosmic-ray accelerators of supernova remnants in the Milky Way. The result was announced in 1996 at the COSPAR space science meeting in Birmingham and published as "Variation of cosmic-ray flux and global cloud coverage – a missing link in solar-climate relationships" (Svensmark and Friis-Christensen 1997).

The title reflected a topical puzzle, that of how to reconcile abundant indications of the Sun's influence on climate (e.g. Herschel 1801, Eddy 1976, Friis-Christensen and Lassen 1991), with the small 0.1% variations in the solar irradiance over a solar cycle measured by satellites. Clouds exert (on average) a strong cooling effect, and cosmic-ray counts vary with the strength of the solar magnetic field, which repels much of the influx of relativistic particles from the galaxy. The connection offers a mechanism for solar-driven climate change much more powerful than changes in solar irradiance.

During the past 10 years, considerations of the galactic and solar influence on climate have progressed so far, and have found such widespread applications, that one can begin to speak of a new paradigm of climate change. I call it cosmoclimatology and in this article I suggest that it is already at least as secure, scientifically speaking, as the prevailing paradigm of forcing by variable greenhouse gases. It has withstood many attempts to refute it and now has a grounding in experimental evidence for a mechanism by which cosmic rays can affect cloud cover. Cosmoclimatology already interacts creatively with current issues in solar–terrestrial physics and astrophysics and even with astrobiology, in questions about the origin and survival of life in a high-energy universe. All these themes are pursued in a forthcoming book (Svensmark and Calder 2007).

How do cosmic rays help make clouds?

The comparisons of data on clouds and cosmic rays, with which the story began, continued to pay off. They confirmed that cloudiness is more clearly linked with solar-modulated galactic cosmic rays than with other solar phenomena such as sunspots or the emissions of visible light, ultraviolet and X-rays (Svensmark 1998). A big step forward came with the realization that the lowest clouds, below about 3 km in altitude, respond most closely to variations in the cosmic rays (Marsh and Svensmark 2000), a counter-intuitive finding for some critics (e.g. Kristjansson and Kristiansen 2000). Figure 2 compares data from the International Satellite Cloud Climatology Project and the Huancayo cosmic-ray station. There is no correlation at high and middle altitudes, but an excellent match at low altitudes.

In figure 3, the correspondence between low clouds and cosmic rays is seen to persist over a longer timescale. A simple interpretation is that there are always plenty of cosmic rays high in the air, but they and the ions that they liberate are in short supply at low altitudes, so that increases or decreases due to changes in solar magnetism have more noticeable consequences lower down.

The involvement of low-level clouds provided an experimental opportunity. The chief objection to the idea that cosmic rays influence cloudiness came from meteorologists who insisted that there was no mechanism by which they could

new theory emerges

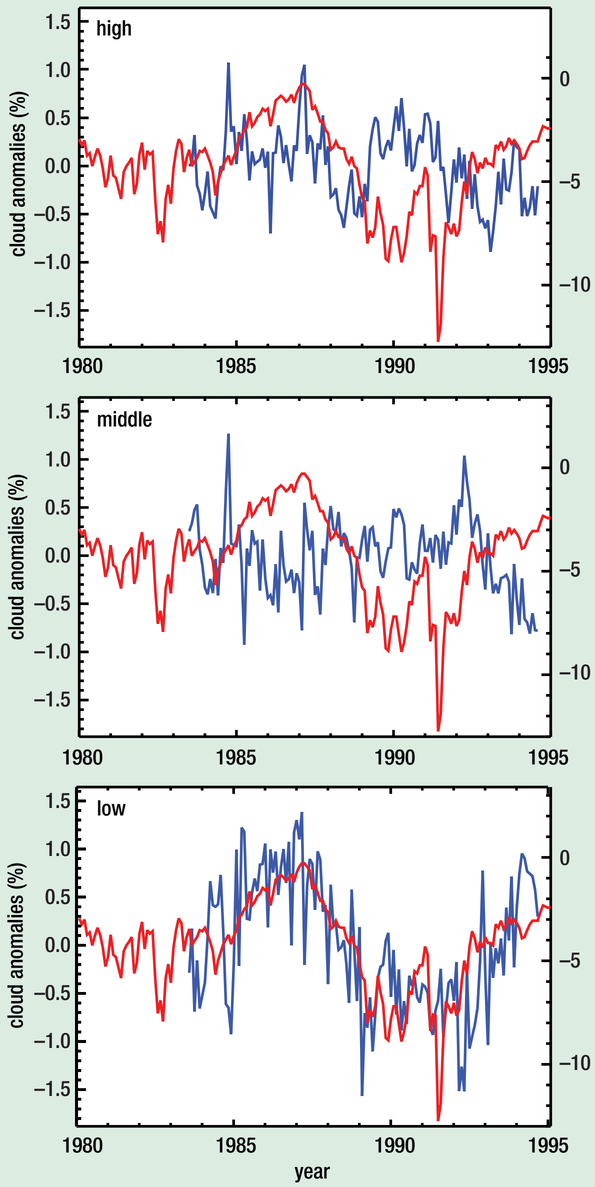
do so. On the other hand, some atmospheric physicists conceded that observation and theory had failed to account satisfactorily for the origin of the aerosol particles without which water vapour is unable to condense to make clouds. A working hypothesis, that the formation of these cloud condensation nuclei might be assisted by ionization of the air by cosmic rays, was open to microphysical investigation by experiment.

Experimental tests

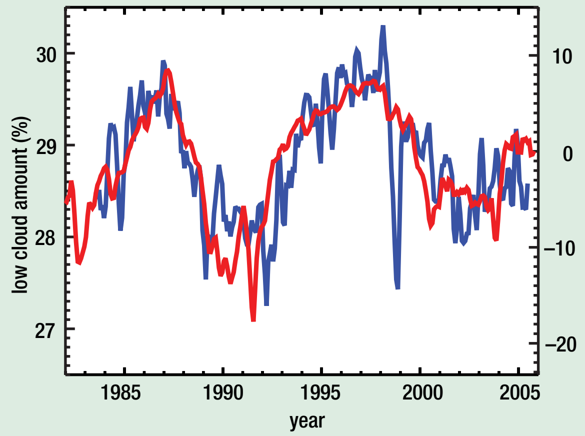
In 1998 Jasper Kirkby at the CERN particle physics lab in Geneva proposed an experiment called CLOUD to investigate the possible role of cosmic rays in atmospheric chemistry. The idea was to use a beam of accelerated particles to simulate the cosmic rays, and to look for aerosols produced in a reaction chamber containing air and trace gases. The temperature and pressure would be adjustable to simulate conditions at different levels in the atmosphere. Kirkby assembled a consortium of 50 atmospheric, solar–terrestrial and particle physicists from 17 institutes to implement it (CLOUD proposal 2000), but regrettably there were long delays in getting the project approved and funded. The go-ahead eventually came in 2006 and the full experiment at CERN should begin taking data in 2010.

Meanwhile, in Copenhagen, the discovery that low-level clouds are particularly affected by cosmic-ray variations suggested that a simpler experiment, operating only at sea-level temperature and pressure, might capture some of the essential microphysics. Instead of a particle beam, we used natural cosmic rays, supplemented by gamma rays when we wanted to check the effect of increased ionization of the air. Our team set up the experiment in the basement of the Danish National Space Center, with a large plastic box containing purified air and the trace gases that occur naturally in unpolluted air over the ocean. Ultraviolet lamps mimicked the Sun's rays. During experiments, instruments traced the chemical action of the penetrating cosmic rays in the reaction chamber. We called the experiment SKY, which means "cloud" in Danish.

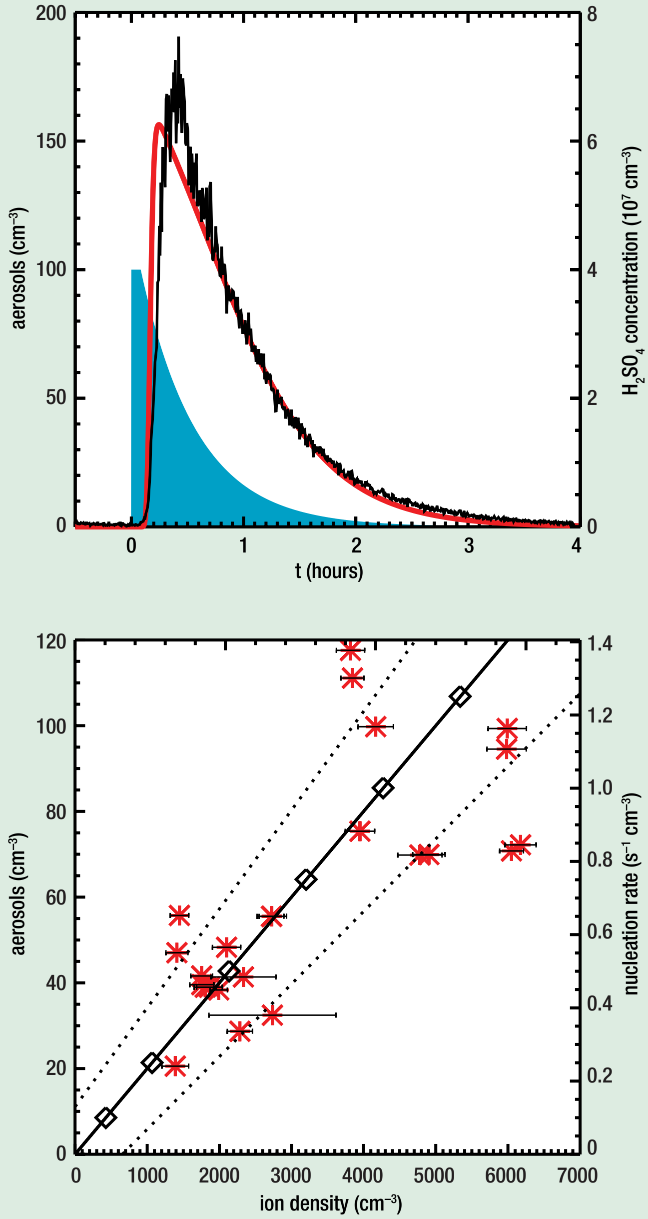
By 2005 we had found a causal mechanism by which cosmic rays can facilitate the production of clouds (Svensmark *et al.* 2007). The data revealed that electrons released in the air by cosmic rays act as catalysts. They significantly accelerate the formation of stable, ultra-small clusters of sulphuric acid and water molecules which are building blocks for the cloud condensation nuclei. Figure 4 shows a typical run. Vast



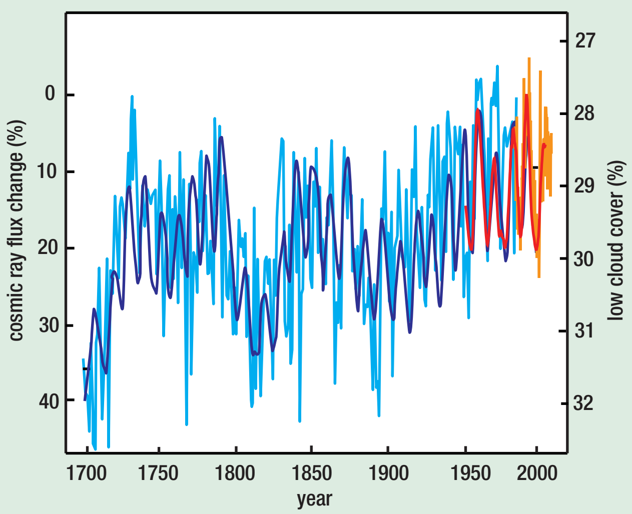
2: At different levels in the atmosphere (high >6.5 km, middle 6.5–3.2 km and low <3.2 km) the blue line shows variations in global cloud cover collated by the International Satellite Cloud Climatology Project. The red line is the record of monthly variations in cosmic-ray counts at the Huancayo station. While there is no match at the higher altitudes, a close correspondence between cosmic rays and clouds low in the atmosphere is plain to see. (Marsh and Svensmark 2000)



3: As in figure 2, the low-cloud comparison extends over a longer period.



4: Creation of the building blocks of cloud condensation nuclei (top) under the influence of galactic cosmic rays is seen in a typical run in the SKY experiment in Copenhagen (Svensmark *et al.* 2007). At time 0 a burst of UV light (simulating solar UV) triggers the formation, from trace gases in the air, of sulphuric acid molecules shown by the blue area and the right-hand scale. Within 10 minutes, great numbers of molecular clusters of sulphuric acid and water molecules larger than 3 nm appear in the reaction chamber (black curve and left-hand scale). The red curve is the fit of a simple model combining rates of production of clusters and their loss on the walls of the chamber. The lower diagram shows the linear relation between ion density and aerosol nucleation. Red stars are the experimental data. In the real atmosphere, in the absence of walls, the clusters would grow in a matter of hours to become cloud condensation nuclei.



5: Changes in the flux of galactic cosmic rays since 1700 are here derived from two independent proxies, ^{10}Be (light blue) and open solar coronal flux (blue) (Solanki and Fligge 1999). Low cloud amount (orange) from figure 3, is scaled and normalized to observational cosmic-ray data from Climax (red) for the period 1953 to 2005 (3 GeV cut-off). Note that both scales are inverted to correspond with rising temperatures. The long-term change in the average flux is as large as the temporary variation within one solar cycle. The change in radiative forcing by a 3% change in low cloud amount over this period can be estimated to ~2 W m^{-2}.

numbers of such microscopic droplets appeared in the air of the reaction chamber, and their production increased proportionately when we used gamma rays to induce more ionization (figure 4, bottom). The speed and efficiency with which the electrons do their work of stitching molecular clusters together took us by surprise. It is a mechanism previously unknown in meteorology and it brings the cosmos into climate studies in a precise microphysical way.

Do clouds really drive climate change?

Low-level clouds cover more than a quarter of the Earth and exert a strong cooling effect at the surface. (For clouds at higher altitudes there is a complicated trade-off between cooling and warming.) The 2% change in low cloud during a solar cycle, as seen in figure 3, will vary the input of heat to the Earth's surface by an average of about 1.2 W m^{-2}, which is not trivial. It can be compared, for example, with 1.4 W m^{-2} attributed by the Intergovernmental Panel on Climate Change for the greenhouse effect of all of the additional carbon dioxide in the air since the Industrial Revolution (Houghton *et al.* 2001).

If cosmic-ray counts merely went up and down with the 11-year cycle of solar activity, there would be no trend in the climate. Systematic records of influx to the Earth's surface go back to 1937. Cosmic-ray changes before then can be seen in the rate of formation of radioactive isotopes such as beryllium-10, or inferred from the Sun's open coronal magnetic field. As seen in figure 5, the various methods agree that there was a pronounced reduction in cosmic rays in the 20th century, such that the maximal fluxes towards the end of the century were similar to the minima seen around 1900. This was in keeping with the discovery that the Sun's coronal magnetic field doubled in strength during the 20th century (Lockwood *et al.* 1999).

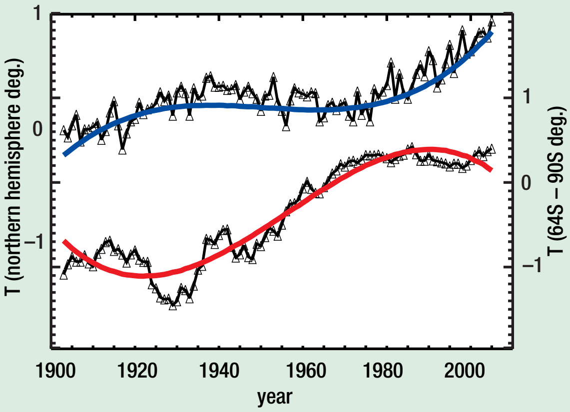
Here is prima facie evidence for suspecting that much of the warming of the world during the 20th century was due to a reduction in cosmic rays and in low-cloud cover. But distinguishing between coincidence and causal action has always been a problem in climate science. The case for anthropogenic climate change during the 20th century rests primarily on the fact that concentrations of carbon dioxide and other greenhouse gases increased and so did global temperatures. Attempts to show that certain details in the climatic record confirm the greenhouse forcing (e.g. Mitchell *et al.* 2001) have been less than conclusive. By contrast, the hypothesis that changes in cloudiness obedient to cosmic rays help to force climate change predicts a distinctive signal that is in fact very easily observed, as an exception that proves the rule.

Cloud tops have a high albedo and exert their cooling effect by scattering back into the cosmos much of the sunlight that could otherwise warm the surface. But the snows on the Antarctic ice

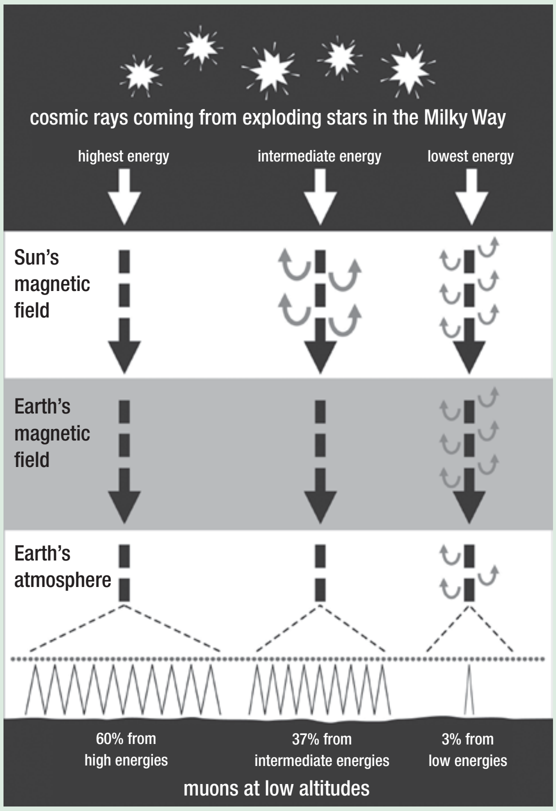
sheets are dazzlingly white, with a higher albedo than the cloud tops. There, extra cloud cover warms the surface, and less cloudiness cools it. Satellite measurements show the warming effect of clouds on Antarctica, and meteorologists at far southern latitudes confirm it by observation. Greenland too has an ice sheet, but it is smaller and not so white. And while conditions in Greenland are coupled to the general climate of the northern hemisphere, Antarctica is largely isolated by vortices in the ocean and the air.

The cosmic-ray and cloud-forcing hypothesis therefore predicts that temperature changes in Antarctica should be opposite in sign to changes in temperature in the rest of the world. This is exactly what is observed, in a well-known phenomenon that some geophysicists have called the polar see-saw, but for which "the Antarctic climate anomaly" seems a better name (Svensmark 2007). To account for evidence spanning many thousands of years from drilling sites in Antarctica and Greenland, which show many episodes of climate change going in opposite directions, ad hoc hypotheses on offer involve major reorganization of ocean currents. While they might be possible explanations for low-resolution climate records, with error-bars of centuries, they cannot begin to explain the rapid operation of the Antarctic climate anomaly from decade to decade as seen in the 20th century (figure 6). Cloud forcing is by far the most economical explanation of the anomaly on all timescales. Indeed, absence of the anomaly would have been a decisive argument against cloud forcing – which introduces a much-needed element of refutability into climate science.

6: The Antarctic climate anomaly during the past 100 years is apparent in this comparison of the annual surface temperature anomalies for the northern hemisphere and Antarctica (64°S–90°S), from the NASA-GISS compilations. The Antarctic data have been averaged over 12 years to minimize the temperature fluctuations. The blue and red lines are fourth-order polynomial fits to the data. The curves are offset by 1 K for clarity, otherwise they would cross and re-cross three times. (Svensmark 2007a)



7: The most important cosmic-ray particles that assist in cloud-making in the lower atmosphere (<2 km), the muons, originate mainly from particles that arrive from the stars with very high energy. The magnetic defences of the Sun and the Earth have little effect on them. The Sun's magnetic field influences the supply of a large minority of muons, but few are obedient to changes in the Earth's magnetic field (adapted from Svensmark and Calder 2007). Ionization of the air by cosmic rays below 2 km altitude is due mainly to penetrating showers from high-energy primary cosmic rays, according to calculations using the Karlsruhe CORSIKA program (Svensmark and Svensmark 2007). The boxes are only intended to illustrate the energy range that the Earth's magnetic field can modulate. For example, at polar regions there is only small influence and if the geomagnetic field disappears, the expected increase in low-altitude ionization is only 3%. Solar activity influences the primaries responsible for about 37% of the ionization. The entire range of primary energies is subject to large changes from the galactic environment of the solar system, including local supernovae, spiral-arm passages, and variations in the star-formation rate.



Does climate follow cosmic-rays?

Figure 5 takes the climate record back 300 years, using rates of beryllium-10 production in the atmosphere as long-accepted proxies for cosmic-ray intensities. The high level at AD 1700 corresponds with the Maunder Minimum (1645–1715) when sunspots were extremely scarce and the solar magnetic field was exceptionally weak. This coincided with the coldest phase of what historians of climate call the Little Ice Age (Eddy 1976). Also plain is the Dalton Minimum of the early 19th century, another cold phase. The wobbles and the overall trend seen in figure 5, between cold 1700 and warm 2000, are just a high-resolution view of a climate-related switch between high and low cosmic-ray counts, of a kind that has occurred repeatedly in the past.

Iciness in the North Atlantic, as registered by grit dropped on the ocean floor from drifting and melting ice, is a good example of the climate data now available. Gerard Bond of Columbia University and his colleagues showed that, over the past 12 000 years, there were many icy intervals like the Little Ice Age – eight to ten, depending on how you count the wiggles in the density of ice-rafted debris. These alternated with warm phases, of which the most recent were the Medieval Warm Period (roughly AD 900–1300) and the Modern Warm Period (since 1900). A comparison with variations in carbon-14 and beryllium-10 production showed excellent matches between high cosmic rays and cold climates, and low cosmic rays and the warm intervals (Bond *et al.* 2001).

For these authors, here was persuasive evidence for what they called "a persistent solar influence". But like many other investigators of astronomical factors in climate change, Bond *et al.* regarded the cosmic rays merely as indicators of the magnetic state of the Sun, varying in a quasi-periodic fashion and affecting solar irradiance. High cosmic rays signified a fainter Sun. Although the problem of how small changes in irradiance could exert so big an influence remained, the proposition that the cosmic rays themselves act on the climate more powerfully, by governing cloudiness, was set aside.

Two of Bond's co-authors, Jurg Beer and Raimund Muscheler of the Swiss Federal Institute of Environmental Science and Technology, use radionuclides to explore solar and climatic

variations in the past. Although the climate changes of the last 12 000 years have indeed followed the cosmic-ray variations, Beer and Muscheler were already co-authors of a paper arguing strongly that the cosmic rays were not the driver (Wagner *et al.* 2001). They had striking evidence from 40 000 years ago, in the Laschamp Event when the geomagnetic field became very weak, in what may have been a failed reversal of the field. Without the screening effect of the geomagnetic field, the cosmic-ray influx increased dramatically. In a Greenland ice core, the counts of beryllium-10 and chlorine-36 atoms produced by cosmic rays went up by more than 50% –and no cooling ensued. The result was compelling because the climate indicators – oxygen-18 and methane abundances – came from the same layers of ice as the radionuclides.

This clear example of the climate failing to follow the cosmic-ray variations was challenging. No quantitative answer was forthcoming until recent calculations traced the origin of the penetrating muons that are responsible for most of the ionization of the air at low altitudes (Svensmark and Svensmark 2007). Then a clear and consistent picture (figure 7) emerged from the CORSIKA program developed for the Karlsruhe Shower Core and Array Detector of Forschungszentrum Karlsruhe, at progressively higher energies of the incoming primary cosmic rays.

Most of the penetrating muons come from relatively rare primaries of such high energy that they are indifferent even to the solar magnetic field. Primaries of low enough energy to be repelled by the geomagnetic field account for only 3% of the low-altitude muons. So it is unsurprising that the near-disappearance of the geomagnetic field, whether in Laschamp-type events or full reversals, should have little effect on climate compared with changes due to solar modulation.

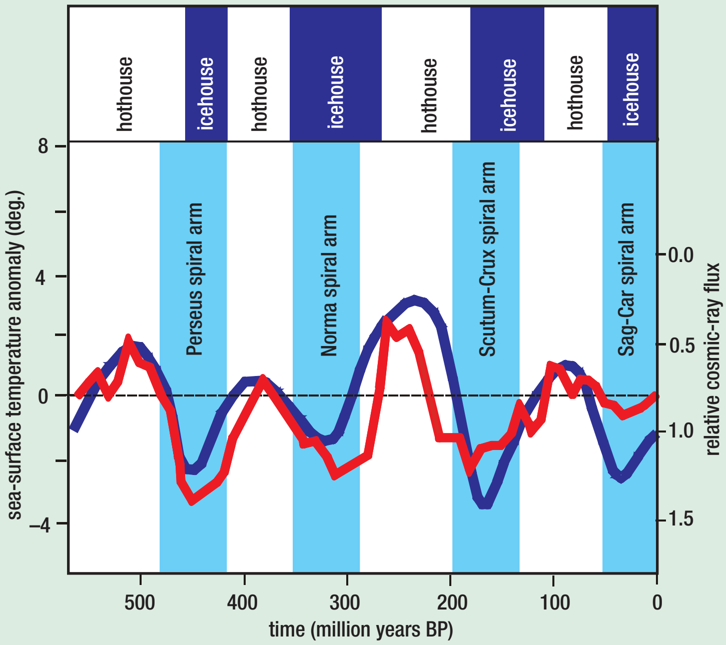
On the other hand, radionuclides are mainly produced higher in the atmosphere, by cosmic rays of lower energy that are more susceptible to variations in the geomagnetic field. Although they remain invaluable for registering cosmic-ray changes due to solar variability, as in figure 5 for example, radionuclides can no longer be taken as infallible guides to climatically effective cosmic radiation, when either the geomagnetic or the galactic environment changes.

Evidence in summary

This article so far has summarized the evidence for the climatic role of cosmic rays, which underpins cosmoclimatology:

- Observations of variations of low cloud cover correlated with cosmic-ray variations;
- Experimental evidence for the microphysical mechanism whereby cosmic rays accelerate the production of cloud condensation nuclei;
- The Antarctic climate anomaly as a symptom of active forcing of climate by clouds;
- Quasi-periodic climate variations over thousands of years that match the variations in radionuclide production by cosmic rays;
- Calculations that remove an apparent difficulty associated with geomagnetic field variations.

From this secure base, we can broaden the horizons of space and time to consider the relevance of cosmic rays to climate change since the Earth was young. The climatic effects of the Sun's quasi-cyclical variations on millennial timescales are seen throughout the Phanerozoic (Elrick and Hinnov 2006). But more emphatic changes in climate become apparent on longer timescales when the galactic environment of the solar system changes and the variations in the cosmic-ray flux are an order of magnitude greater than those due to the Sun.



8: Four switches from warm "hothouse" to cold "icehouse" conditions during the Phanerozoic are shown in variations of several degrees K in tropical sea-surface temperatures (red curve). They correspond with four encounters with spiral arms of the Milky Way and the resulting increases in the cosmic-ray flux (blue curve, scale inverted). (After Shaviv and Veizer 2003)

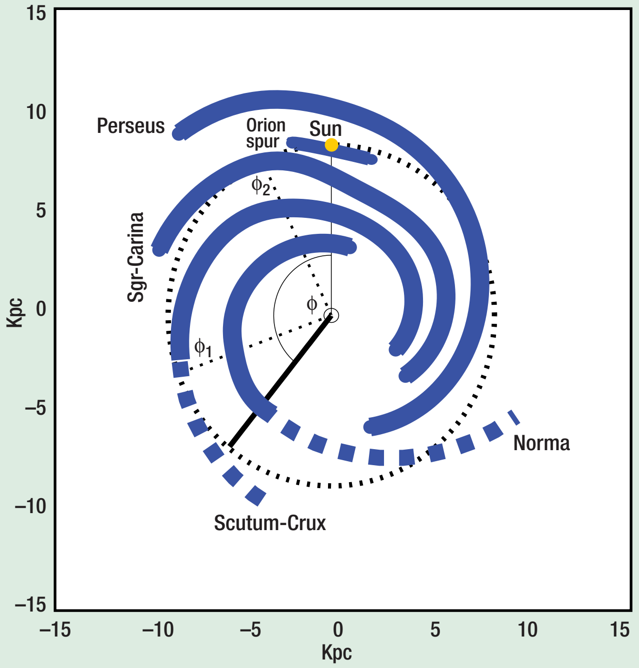
What drove the big alternations?

Large, slow swings, to and fro between ice-free and glaciated climates, are evident in the geological record of the past 550 million years. Efforts went into using the greenhouse-warming paradigm to try to account for these changes, but the pattern was wrong. There were four alternations between hothouse and icehouse conditions during the Phanerozoic, while reconstructions of atmospheric carbon dioxide show just two major peaks (Cambrian-Devonian and Mesozoic) and troughs (Carboniferous-Permian and Cenozoic). A more persuasive explanation comes from cosmoclimatology, which attributes the icehouse episodes to four encounters with spiral arms of the Milky Way galaxy, where explosive blue stars and cosmic rays are more concentrated.

Nir Shaviv, an astrophysicist at the Hebrew University in Jerusalem, pioneered this interpretation several years ago (Shaviv 2002). The relative motion of the spiral arm pattern with respect to the solar orbit around the galactic centre was uncertain, but Shaviv found that reasonable assumptions gave a good fit with the climatic record, in cycles of ~140 million years. He found independent evidence linking the icehouse episodes with high cosmic radiation in a ~140 million-year cycle of clustering of the apparent exposure ages of iron meteorites by cosmogenic potassium isotope ratios ($^{41}K/^{40}K$). Later, Shaviv joined forces with a geologist, Jan Veizer of the Ruhr University and the University of Ottawa, to refine the analysis using a large database on tropical sea-surface temperatures, as seen in figure 8 (Shaviv and Veizer 2003). The matches between spiral-arm encounters and icehouse episodes are as follows:

- Perseus Arm: Ordovician to Silurian Periods;
- Norma Arm: Carboniferous;
- Period Scutum-Crux Arm: Jurassic to Early Cretaceous Periods;
- Sagittarius-Carina Arm: Miocene Epoch, leading almost immediately (in geological terms) to
- Orion Spur: Pliocene to Pleistocene Epochs.

The Jurassic to Early Cretaceous icehouse is a matter of special interest. Until recently, geologists considered the Mesozoic Era to have been warm throughout, so when Shaviv first saw that his analysis needed that icehouse, he was disappointed. Then he was reassured by recent reports of signs of ice-rafting, just as required. The first clear evidence for glaciers ~140 million years ago (Australia, Early Cretaceous) was published in 2003. That a story should become better as the data improve is characteristic of a successful paradigm. For the greenhouse theory of climate change, on the other hand, the Mesozoic glaciation was bad news, because carbon dioxide concentrations in the atmosphere were high at the time. The comparative mildness of the Mesozoic icehouse may have been due to the carbon dioxide (Royer et al. 2004) or perhaps to a relatively quick crossing of the Scutum-Crux Arm.



9: The Sun's motion relative to the galaxy's spiral arms over the past 200 million years is defined by changes in the angle ϕ. The most recent spiral-arm crossings ϕ_1 and ϕ_2 were at ~100° and ~25°. Climatic data show rhythmic cooling of the Earth whenever the Sun crossed the galactic midplane, where cosmic rays are locally most intense. From these geophysical data, the astrophysical data shown in table 1 can be inferred. (Svensmark 2006a)

1: What does the climate tell us about the Milky Way?

Mass density	
ρ_{local} (now)	$0.115 \pm 0.1\,M_\odot pc^{-3}$
$\bar{\rho}$	$0.145 \pm 0.1\,M_\odot pc^{-3}$
$\rho_{arm}/\rho_{interarm}$	≈1.5–1.8
Timing of spiral-arm crossings	
Sgr-Car	34±6 Myr
Scrutum-Crux	142±8 Myr
Pattern speed	
Ω_P	$13.6 \pm 1.4\,km\,s^{-1}kpc^{-1}$
ϕ_1	25±10°
ϕ_2	100±10°

Properties of the Milky Way derived from variation in Earth's temperature during the last 200 million years (Svensmark 2006a). Due to the solar system's position within the Milky Way it is difficult to obtain fundamental dynamical parameters by astronomical observations. The arm/inter-arm ratio cited here is in the range seen in other spiral galaxies. The pattern speed is the angular velocity of the spiral arms.

Turn the reasoning around, and geophysical data can help to refine the astronomical description of the galaxy. When the fossil organisms in carbonate rocks were alive in the near-surface water they were, in effect, cosmic-ray telescopes, registering the flux changes as the inverse of the sea-temperature changes logged by oxygen-18 counts. Besides the effects of spiral-arm encounters, the oxygen-18 record shows higher-frequency changes in temperature associated with the Sun's oscillations about the galactic mid-plane, and the temperatures set tight limits on the dynamics (Svensmark 2006a).

The coolest phase every 34 Myr or so corresponds with a crossing of the mid-plane, where cosmic rays are locally most intense, and it is well dated by geologists. The concentrations of mass near the mid-plane affect the Sun's oscillations, and they are different inside and outside the spiral arms. Figure 9 gives an overview of the Milky Way and the Sun's orbit for the past 200 Myr. Only one combination of key numbers describing the galactic environment gives correct cross-plane motions of the Sun needed to match the climate changes recorded by the fossil organisms during that period. The results of the analysis, seen in table 1, fall inside a wide range of previous suggestions from astronomical data, but narrow them down decisively from a geophysical point of view.

Why did the Earth freeze over?

The discovery of widespread glaciation in the tropics during the Proterozoic, in the Snowball Earth episodes around 2300 million and 700 million years ago, set a conundrum for traditional climate theory. To be explained is not only what might have caused such events, but why they occurred just when they did, when the Earth was 50% and 15% of its present age. And why was there a long warm interval between them with no icy interludes like those seen in the past 550 million years? Again, cosmoclimatology provides a cosmic timeframe that promises to explain it all.

Increases in the rate of star formation in the Milky Way galaxy, associated with close encounters with the Magellanic Clouds, must have affected the cosmic-ray flux to the Earth, because of the increased number of supernovae – as seen, for example, in starburst galaxies. As for the climatic consequences, Nir Shaviv in Jerusalem pointed out that the Early Proterozoic Snowball Earth episode coincided with the highest star-formation rate in the Milky Way since the Earth was formed, in a mini-starburst 2400–2000 million years ago (Shaviv 2003a).

In data from Rocha-Pinto *et al.* (2000), Shaviv noted star formation at twice the present rate during the Early Proterozoic, followed by a billion-year lull when the rate dropped to half of what it is now. That can explain the long ice-free interval in the Proterozoic, when visits to the spiral arms failed to deliver enough cosmic rays to create icehouse conditions. Although the Rocha-Pinto data showed a moderate restoration of the star-formation rate in time for the later Snowball Earth events, more striking results came from Marcos and Marcos (2004). These authors noted a peak around 750 million years ago as the highest rate of star formation during the past 2 billion years and remarked on its aptness for the Snowball Earth scenario.

Going back 4000 million years, to when the Sun and Earth were young, the puzzle is why the Earth was not frozen then. The Sun's luminosity was, according to the standard model of solar evolution, less than 75% of its present value, the Earth's mean surface temperature should have been 25 K cooler than now. Yet there is mineral evidence for liquid water 4400 million years ago, and the oldest remains of life, 3800 million years old, are found in sediments from an ancient sea. This paradox of the faint young Sun has been discussed for more than 30 years.

However, revised solar models suggest a near-absence of cosmic rays (Shaviv 2003b, Svensmark 2003). With a far more vigorous solar wind, the young Sun would have reduced the influx to such a small fraction of the present rate that, in the cosmoclimatological interpretation, the Earth would not have had much cloud cover. That would compensate for much of the weakness of the solar irradiance, and so reduce the contribution required from greenhouse gases.

A surprising by-product of this line of enquiry is a new perspective on the changing fortunes of life over 3.5 billion years (Svensmark 2006b). By combining calculations about the changing ability of the Sun to repel cosmic rays with data on the changing star-formation rate, one can reconstruct the resulting cosmic-ray flux. Figure 10 compares the reckonings with data from an entirely different source, concerning variability in the overall productivity of the biosphere, gauged by the proportion of carbon-13 in carbonate rocks. The biggest fluctuations in productivity between boom and bust coincided with the highest cosmic-ray rates. Conversely, during the billion years when star formation was slow and cosmic rays were less intense, the biosphere was almost unchanging in its productivity. This reveals a link more subtle than any straight-

forward idea of, say, a warm climate being life-friendly or a cold climate deadly. It may be related to the better recycling of trace elements in cold conditions (see Svensmark 2006b).

What remains for investigation?

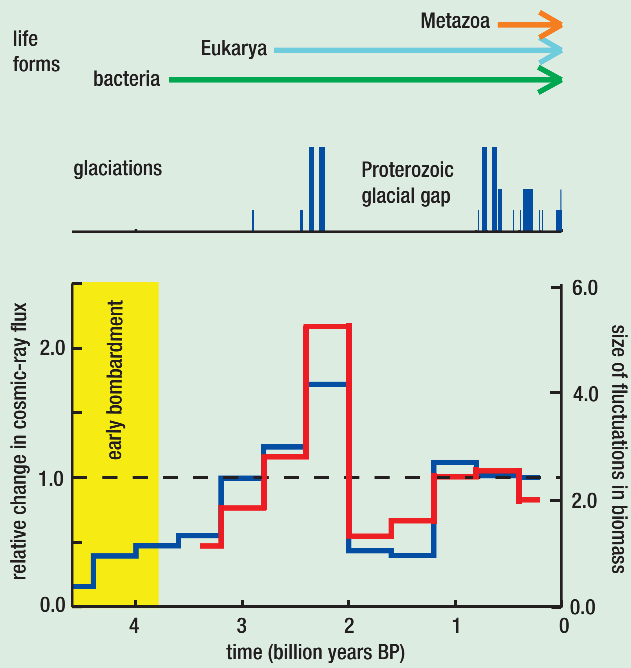
The past 10 years have seen the reconnaissance of a new area of research by a small number of investigators. The multidisciplinary nature of cosmoclimatology is both a challenge and an opportunity for many lines of inquiry. The interaction between different branches of science is no mere exchange of text-book information, but takes place at the cutting edge of discovery. An example comes from the astrophysics of Gould's Belt, the tumultuous region of the galaxy into which the solar system has wandered.

The possibility that cosmic rays from a nearby supernova provoked the onset of northern glaciation 2.75 million years ago was mooted by Knie *et al.* 2004. This is of special interest because of the replacement of some African forests by grassland and the emergence of human beings. The earliest known stone tools date from 2.6 million years ago. Whether or not the particular event cited by Knie *et al.* was responsible, gamma-ray astronomers are alert to the need to identify supernova events within Gould's Belt during the past few million years if climate change on that timescale is to be fully understood.

Better knowledge of the spiral arms and star-formation history of the galaxy should clarify the climate connection over longer spans of time, and ESA's Gaia mission can be expected to make a big stride forward. At the same time, the onus falls on Earth scientists to improve knowledge of climate history before 200 million years ago with an on-shore drilling programme to match the scope and success of ocean-floor drilling (Soreghan *et al.* 2005). These very different ventures in astronomy and geophysics should converge, and also be of great interest to palaeontologists and evolutionary biologists.

The Milankovitch changes in the Earth's attitude and orbit show up persistently in the oxygen-18 record of recent ice ages, notably at high latitudes. They pose conundrums for both the greenhouse and cosmic-ray theories of climate change. Large rises in temperature within the glacial periods, related to cosmic-ray decreases, do not melt the main ice sheets. Terminations leading to interglacial conditions seem to need an insolation trigger, whether from obliquity (40-kyr cycle) in the early Pleistocene or ellipticity (100-kyr cycle) in the late Pleistocene. To account for high rates of deglaciation associated with particular insolation frequencies, amplifying mechanisms on offer include surges in atmospheric carbon dioxide (Shackleton 2000) and changes in ice-sheet geography (Raymo et al. 2006). In Copenhagen we hope to use simple climate models of the glacial cycles to test whether geographical factors, including ice-sheet extent and sea-level changes, may account for variable sensitivity to, or resonance with, climate forcing by orbital changes, clouds or greenhouse gases.

10: When life began about 3.8 billion years ago, the cosmic-ray flux (blue curve) was very low, because of the vigour of the solar wind. Complex life forms (single-cell eukarya and multi-cell metazoa) rose to success during global glaciations, which coincided with high cosmic rays linked to high star-formation rates. The red curve shows the size of variations in the productivity of the biosphere, which was most erratic when the cosmic-ray flux was greatest. (Svensmark 2006b and references therein)



The physics of the Sun and the heliosphere runs through the story on all timescales from the early Earth to the present day. Whatever the verdict may be about the relative importance of cosmic rays and greenhouse gases in current and future climate change, there is an obvious need to predict future solar behaviour better, by clearer observations of the magnetic field at the Sun's poles. There are already strong hints that taking cosmic rays into account should help to improve the annual forecasts of the Asian monsoon.

The complete checklist of future research concerning cosmic rays and climate ranges from more thorough investigation of aerosol chemistry (as promised by CLOUD) to the implications for astrobiology and the search for alien life. Besides the traditional "Goldilocks" comfort zone set by stellar irradiance, it now seems clear that stellar winds and magnetism are crucial factors in the origin and viability of life on wet Earth-like planets. So are the ever-changing galactic environments and star-formation rates. The tropical glaciers of Snowball Earth tell us that survival was a close-run thing, even here. ●

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